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Theoretical analysis of channeling atom through a mono-mode hollow optical fiber

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Abstract : Atom location, atom dipole polarisation and the order of excited mode are the principal factors governing the structure influences in a hollow optical fiber such as, enhancement or complete suppression of dipole emission rate in presence of the structure mode. In a hole diameter of the optical fiber of the order of 2–10 μm, only the fundamental mode with cut-off frequency 0.3 PHz can exist. This means that the system operates as an exact mono-mode optical fiber and the atom propagation maintains coherence. In the slow atom approach, the electric dipole moment vector is strained by the structure mode to ensure the electric field vector at the instantaneous position of the dipole. Therefore, the polarisation gradient of slow atom controls every effect emerging in the presence or absence of the structure mode. The influence of the slow atom approach is examined with reference to certain cases, involving sodium atoms in hollow mono-mode optical fiber. The role of the fundamental mode in the atomic motions is considered.

Keywords : Hollow optical fiber, mono-mode, decay emission rate, Rabi frequency, optical forces

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1. Introduction

The established domain of atom-wave optics is enriched by a new branch of quantum optics known as atom optics, which deals with manipulating atom trajectories along with exploiting the wave properties of neutral atoms [1,2]. The wave mechanical aspects manifest themselves in the coherent propagation of atoms within atom-optical devices such as lenses, mirrors, beam-splitters and atom interferometers and it deals with new 'dissipative' element such as heating, cooling and trapping [3,4], which have no similarity with any other kinds of optics.

Recently, advances in micro-fabrication technology as well as in the production of intense tunable lasers, have refreshed activity in atom optics. Both have led to significant progress in the control of neutral atoms using laser light [5–7]. The channelling of atoms through hollow waveguide by light forces, is another important sub-field of atom optics. This channelling can occur easily and efficiently in a manner similar to the propagation of light in the fiber. This has been a target of extensive theoretical and experimental studies since 1993 when it was predicted independently by two groups [8,9].

In order to achieve an accurate atomic interferometry using atomic waves, two major obstacles should be removed. The first one is related to the weak coherence of the atom waves. The concept of the coherence of atomic matter wave can be introduced in straight resemblance with the light waves, the light beam being replaced by the atomic matter beam. But we should recognise that there are many essential differences between the two kinds of coherence. Initially, atoms have internal structure and then the decay transition influences the coherence of atomic matter beam. In addition, there is a collision between atoms and, in contrast to the conventional optics, the free space dispersion relations are different because atoms have mass, while light is

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massless. Finally, the atom may be brought to rest while light travels at the constant speed relative to all inertial observers [10]. The second problem causes difficulty in selecting a particular mode to excite the atom. However, to remove these obstacles, we suggest the use of a mono-mode waveguide constructed in such a way as to allow only the fundamental mode to propagate, a method similar to the widely used technique in fiber optics [11].

The plan of this paper is as follows. In Section 2, we outline a background about the different ways of channeling atoms in literature. In Section 3, we derive the electromagnetic field inside the mono-mode optical fiber and determine the properties of the main factors in such fiber. In Section 4, we evaluate the decay emission rate in absence of mode structure. In Section 5, we consider the slow atom approach and calculate the decay emission rate, Rabi frequency and optical forces obeying the conditions of this approach. We also examine the dynamics of atoms within such fiber and discuss the influences on the atomic trajectory when a structure mode is excited. Section 6 contains the main conclusions and provides further comments.

2. Theoretical model

Many methods have been proposed for channeling free atoms. The first method is atomic mirrors, which includes two ways : the direct reflection from a surface [12] and reflection potentials induced by optical electromagnetic fields which based on the evanescent wave of a totally reflected light beam [13]. The second method is atomic pipes based on a hollow optical fiber [8,9].

The idea of the latter method encompasses a combination of two experimental techniques, namely the channeling of atoms by means of laser light [13] and the channeling of light by means of optical fiber [11]. There are two types of optical fiber walls : perfect conductor [7] and dielectric medium [5]. So, there are two mechanisms to channel atoms down a hollow optical fiber, firstly the direct propagating of light down the hollow region (or grazing incident mode) for the perfect conductor fiber walls and secondly, the evanescent electric field for the dielectric walls. The perfect conductor configuration was proposed by Ol'Shanii *et al* in 1993 [8] and was demonstrated experimentally by Renn *et al* [14], while the evanescent field configuration was propounded by Savage *et al* in 1993 [9] and extended by Marksteiner *et al* [6] and Ito *et al* [5]. It was also demonstrated experimentally by the same Renn *et al* [15].

On the other hand, the optical fiber may be multi-mode or mono-mode. The multi-mode fiber is relatively easy to fabricate and can be treated using ray optics [11] while the mono-mode fiber is hard to fabricate as the coupling of light (and atoms) is harder and the ray optics approximation breaks down. Then, one must use the wave optics approach. In the wave optics, one assumes that the wave is confined within the hole of the fiber with a standing wave pattern in the lateral direction that falls to zero at the hole edge and an integral number of half-wavelengths are fitted into the hole width [16].

In the present work, we have used the configuration suggested by Ol'Shanii *et al* [8], which is based on the grazing incident mode. Therefore, the laser frequency should tune to the red side (above atomic resonance) in order to attract the atoms to the high power region at the center of the hollow optical fiber [7,17].

Most of the previous studies on atom fiber have concentrated on large dimensions, with multi-mode operation. For example, the hole diameter of the optical fiber in Renn *et al* [14] experiment was around 40 μm which is large enough to allow propagation of many modes within the optical fiber. Consequently, dipole emission rate approaches the free space value. Little work has been done on atom fibers with sub-wavelength dimensions where the dipole emission rate may only be mediated by a few feasible modes [18].

In this contribution, we consider a mono-mode hollow optical fiber, which allows propagation of only one mode. Hence, the hole diameter must be of the order of the 2–10 μm. This means that only the fundamental mode (the lowest order mode) TE_{11} can exist. Hence, the limit of mono-mode operation depends on the lower limit of guided propagation of the TE_{11} mode. The cut-off frequency for TE_{11} mode in hollow optical fiber occurs at $f_{11} \approx 0.3$ PHz.

In addition to the mono-mode property, this study is the first effort to consider the channeling of atom by the transverse electric field *TE* modes leading to quite different features of the channeling atom as will be seen later.

3. Field distribution in a mono-mode fiber

The structure we are concerned with, is a hollow optical fiber of diameter $r = 2a = 0.5\lambda$ (where $\lambda = 589$ nm). The structure is postulated to be perfectly conducting. The travelling wave-modes of such system are well known [19] and have been quantised for a multi-mode type that involves summation of both s-polarized (TE) and p-polarized (TM) modes by Rippin and Knight [20]. For a mono-mode type, only the TE_{11} mode can exist and the mode's electric functions can be written as

$$E^s(11,k,\mathbf{R},t) = \frac{-2i\pi f^s_{11k} a^2 E^s_0}{(\chi^s_{11})^2} e^{\pm i\phi} e^{i(2\pi f^s_{k11} t-kz)}$$

$$\frac{\chi^s_{11}}{a} J_1'\left(\chi^s_{11}\frac{r}{a}\right)\hat{\phi} - \frac{i}{r} J_1\left(\chi^s_{11}\frac{r}{a}\right)\hat{r} \tag{1}$$

where k is the longitudinal wave-vector and J_1, and J_1' are the order one Bessel function and its first derivative respectively, while f^s_{11k} is the mode frequency given by

$$f_{11k} = \frac{c}{2\pi}\left| k^2 + \left| \frac{\chi^s_{11}}{a} \right.\right. \tag{2}$$

where χ^s_{11} is the zero of J_1' function χ^s_{11} has the smallest root of all the Bessel function derivatives where the first root of J_l' is $\chi^s_{11} = 1.84$. Finally, in eq. (1), E^s_0 is the TE_{11} mode normalization factor obtained as

$$E^s_0 = \left[\frac{(1.84)^2\hbar}{2\varepsilon_0 V a\left((1.84)^2-1\right) J_1^2(1.84)}\right] \tag{3}$$

where V is the quantization volume. The cut-off frequency and cut-off wavelength of this lowest mode are

$$f_c = \frac{1.84c}{2\pi a}, \quad \lambda_c = \frac{2\pi a}{1.84} = 3.41a \tag{4}$$

Using $a = 0.5\lambda$, the cut-off frequency and cut-off wavelength of this particular mode are, $f_c \approx 0.3$ PHz and $\lambda_c \approx 1$ μm respectively.

4. Decay in absence of the structure mode

It is well known that when a quantum mechanical system radiates spontaneously in a confined space, both the dipole emission rate and the energy levels experience changes [21]. The dipole emission rate of the dipole emitter located in a confined space, becomes position-dependent. The dipole emitter is modelled as a single two-level atom with the ground $|g\rangle$ state and the excited $|e\rangle$ state separated by the transition frequency $f_0 = (E_e - E_g)/h$. If an atom is in an excited state and the field contains no photon (coupled to vacuum field), this state will release its energy by spontaneously radiating a photon.

However, for the situation of multi-mode type, Rippin and Knight [20] have evaluated the modification of the dipole emission rate in a hollow optical fiber as well. For a mono-mode type, the formula reduces to

$$\frac{\Gamma(R_\perp)}{\Gamma_0} \quad \frac{3\lambda}{(2\pi a)}\left[\Theta^\phi_{11}(R_\perp) + \Theta^r_{11}(R_\perp)\right], \tag{5}$$

where Γ_0 is the dipole emission rate in free space and is given by

$$\Gamma_0 = \frac{8\pi^2\mu^2}{3\hbar\varepsilon_0\lambda_0^3}, \tag{6}$$

and Θ functions are defined as

$$\Theta^r_{11}(R_\perp) = \frac{2a^2 \Lambda_{11}}{J_1^2(1.84)/r^2} J_1^2\left(1.84\frac{r}{a}\right) \tag{7}$$

$$\Theta^\phi_{11}(R_\perp) = \frac{2(1.84)^2}{J_1^2(1.84)} J_1'^2\left(1.84\frac{r}{a}\right), \tag{8}$$

where we have defined Λ_{11} by

$$\Lambda_{11} = \frac{\left[(2\pi a/\lambda_0)^2 - (1.84)^2\right]^{-1/2}}{\left[(1.84)^2 - 1\right]} \tag{9}$$

5. Slow atom approach

The hollow optical fiber acts as a channel for both light and atoms. Two different approaches exist for dealing with the physical cases. Firstly, the high-speed atom approach which leads to no change in the dipole orientation for polarized atoms (*i.e.* we can assume that the state of dipole orientation does not depend on the excitation of a cavity mode). Then, we can follow the old established pattern in which the dipole moment vector is either adjusted parallel or perpendicular to the longitudinal axis. The important intention here, is to consider the dipole emission rate and atom dynamics for dipoles polarized in given directions, before they enter the optical fiber and so independent on the excited mode [22].

Secondly, the slow atom approach, where the atom's transit time can indeed be longer than that of a typical decay. Hence, the electric dipole moment vector is strained by the structure mode to follow the electric mode vector at the instantaneous position of the dipole. This means that the electric dipole of a moving atom steadily adjusts its direction along the electric mode vector of the excited structure mode. According to this approach, the polarization gradient controls all the cavity QED effects arising in the absence of the structure mode such as dipole emission rate or in the presence of the structure mode such as radiation forces [7]. In the following subsections, the effects of the polarization gradient on emission rate and radiation forces are discussed.

5.1. Decay in the slow atom approach :

In the presence of any excitation modes, the dynamic state of the atom will be altered and the dipole emission rate becomes dependent on the excited mode. We are considering the situation in which the specific electric dipoles respond to the excited modes by vibrating along the direction of the local mode. We note that the slow atom approach has significant results for typical cases involving sodium atoms in a mono-mode optical fiber. This approach has led to important consequences for other cases in which the fundamental order *s*-polarized TE_{11} mode is excited. This specific mode has the attractive property of having the lowest cut-off frequency with the order of azimuthal component greater than zero; so, it be able to possess orbital angular momentum (OAM). In addition, electric field of the TE_{11} mode in contrast to the *p*-polarised modes, is not coupled to the longitudinal axis. The latter feature makes this mode ideal candidate in the context of cooling process by a one-dimensional molasses configuration involving a pair of counter-propagating optical fiber modes.

Applying the slow atom approach in the presence of the TE_{11} mode means that the decay emission should be written as

$$\Gamma(r) = \Gamma_x \sin^2\beta(r) + \Gamma_y \cos^2\beta(r), \tag{10}$$

where $\beta_{11}(r)$ is the adjustment angle of the electric mode vector at the point r

$$\beta_{11}(r) = \tan^{-1}\left(\frac{E_y}{E_x}\right) \tag{11}$$

wher E_x and E_y are the magnitude of the transverse components of the electric field.

The variation of the angle $\beta_{11}(r)$ for particular mode TE_{11} across a diameter of a hollow optical fiber is shown in Figure 1. This figure shows clearly that for this particular mode, the angle of adjustment is 90° at the center of the hole (pure normal polarisation) and monotonically decreases across the diameter to zero at the surface.

In Figure 2, we plot the change of the dipole emission rate across a diameter of the hollow optical fiber. The calculations are based on eq. (10) using eqs. (3) to (9).

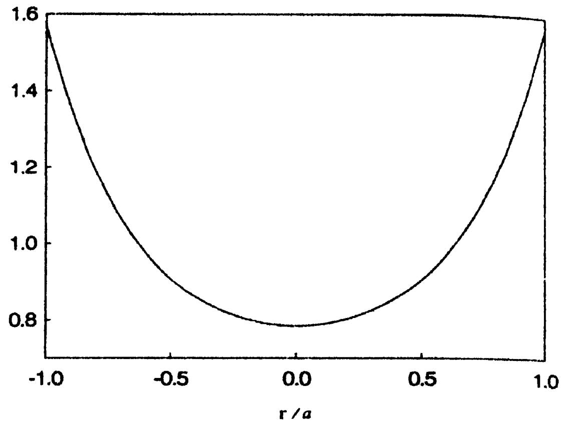

Figure 1. Variation (across a diameter) of the orientation angle for electric dipole which oscillates along the local electric mode direction of an excited

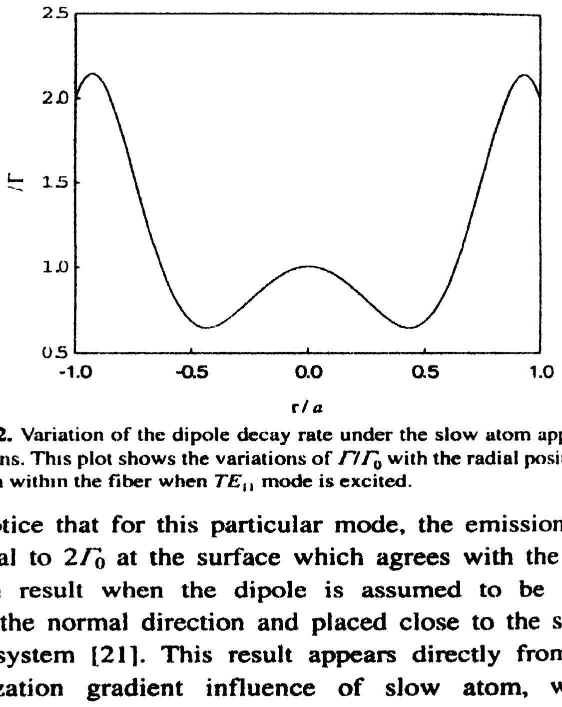

Figure 2. Variation of the dipole decay rate under the slow atom approach conditions. This plot shows the variations of Γ/Γ_0 with the radial position of the atom within the fiber when TE_{11} mode is excited.

We notice that for this particular mode, the emission rate is equal to $2\Gamma_0$ at the surface which agrees with the well known result when the dipole is assumed to be fixed along the normal direction and placed close to the single plate system [21]. This result appears directly from the polarization gradient influence of slow atom, which constrains the dipole to remain normal to the surface. Consequently, the polarization gradient leads to observable changes in the emission rate especially for the slow atomic velocities. Finally, it is very important to recognize that because of a hole diameter value of $r = 2a = 0.5\lambda$ picked for explication objectives in Figure 2, the dipole emission rate distributions appear only from the fundamental mode TE_{11}.

5.2. Light forces in slow atom approach :

The light forces are explained with reference to two-level atom subject to a near-resonant laser light. Such atom suffers from two different forces: scattering forces due to absorption of the light by the atom followed by its decay emission and a reactive forces due to absorption followed by stimulated emission. The scattering forces relate to the heating and cooling of atoms while the reactive forces relate to the trapping of atom. However, the total light forces acting on an atom of transition frequency f moving in the vacuum hole of such structure is known. Detailed consideration of the mode phase $\theta(\boldsymbol{R})$, the detuning $\Delta(\boldsymbol{R},\boldsymbol{V})$ and the orbital angular momentum (OAM) properties exhibited by such structure has been given in Ref. [23]. As pointed out earlier, the main emphasis in this study has been directed to the role of mono-mode operation under the slow atom approach conditions. In this case, the total light forces in low power limit can be obtained by [23]

$$\boldsymbol{F}_{\text{total}} = \frac{\hbar}{2}\left\{\frac{2\Gamma S(\nabla\theta) - \Delta(\nabla S)}{1+S}\right\} = \boldsymbol{F}_{\text{SC}} + \boldsymbol{F}_{\text{RE}}, \tag{12}$$

where $\boldsymbol{F}_{\text{SC}}$ corresponds to the first term, and is identified as the scattering force along the wave propagation and F_{RE} corresponding to the second term, is identified as the reactive force. The latter force can directly be derived from a potential of the form $U = (1/2)\hbar\Delta\ln(1 + S)$ where $F_{\text{RE}} = -\langle\nabla U\rangle$. In view of Ref. [23], mode phase $\theta(R)$, the dynamic detuning $\Delta(\boldsymbol{R},\boldsymbol{V})$with the TE_{11} mode excited at frequency f^{s}_{k11}at velocity V, are given by

$$\theta(\boldsymbol{R}) = (\pm\hat{\phi} + k\hat{z});\ \Delta(\boldsymbol{R},\boldsymbol{V}) = \Delta_0 + \nabla\theta\ , \tag{13}$$

where $\hat{\phi}$ and $\hat{z}$ are the usual unit vectors in cylindrical coordinates system and $\Delta_0 = (f^{s}_{k11}/2\pi) - (f_0/2\pi)$ is the static detuning of the light from atomic resonance. In eq. (12), $S(\boldsymbol{R},\boldsymbol{V})$ is defined as the saturation parameter, which is written as

$$S = \frac{2\Omega}{\Delta^2 + \Gamma^2} \tag{14}$$

where Ω is the Rabi frequency for an electric dipole μ in the TE_{11} channeling mode, which can be given by

$$\Omega(r) = \frac{\alpha\mu.\boldsymbol{E}^{s}(1,1,k,r,t)}{} \tag{15}$$

where α is a complex amplitude factor which is related to the power P of the channeling mode as [24]

$$|\alpha|^2 = \frac{PL}{hcf}, \tag{16}$$

From eq. (1), it is easy to see that the channelling mode possesses two vector components. In the slow atom approach, as we mentioned earlier, the channelling mode has been set up, the average atomic dipole moment vector at any given point aligns itself forward, and ensure the oscillations of the local electric mode vector. The suitable Rabi frequency in this case is thus given as

$$\Omega(r) = \left(\frac{4\pi^2\mu^2 LP}{h^3 cf}\right)^{1/2} E^{s}(r). \tag{17}$$

where μ and E^{s} are the magnitude of these vector. Using eqs. (15) and (16), we can write the square of Rabi frequency in the following form :

$$\frac{\Omega^{s}_{k11}}{\Omega_0} \quad \frac{(1.84)\left[J_0^2\left(1.84\frac{r}{}\right) + J_2^2\left(1.84\frac{r}{}\right.\right.}{J_1\left(1.84\sqrt{(1.84)^2 -}\right.} \tag{18}$$

where Ω_0 is the free space Rabi frequency, which is given as

$$\Omega_0 = \left(\frac{P\mu^2}{2\pi^2 a\hbar^2\varepsilon_0 c}\right)^{1/2} \approx 8.56\times10^9\,\text{s}^{-1} \tag{19}$$

To illustrate this theoretical model, we consider the case of sodium atom in a mono-mode hollow optical fiber with radius a = 0.5λ. The Na mass is $M = 23 \times 1.67 \times 10^{-27}$ kg, the transition wavelength is λ = 589 nm with $\Gamma_0 = 6.13 \times 10^7$ s^{-1}. The typical mode parameters considered here are : a static detuning $\Delta_0 = 6 \times 10^2\Gamma$, the free space Rabi frequency $\Omega_0 = 1.39 \times 10^2\Gamma_0$ and the TE_{11} mode has been excited by a laser power $P \approx (10^{-7}/\pi a^2)$ Watt as chosen by Renn *et al* [14]. With the TE_{11} as defined above and with f_0 corresponding to λ = 589 nm, it is easy to determine the value of the longitudinal wave-vector k using eq. (2).

Figure 3 displays the distribution of the Rabi frequency across the hole diameter under the above conditions. The minimum power is located at the center (r = 0). Therefore,

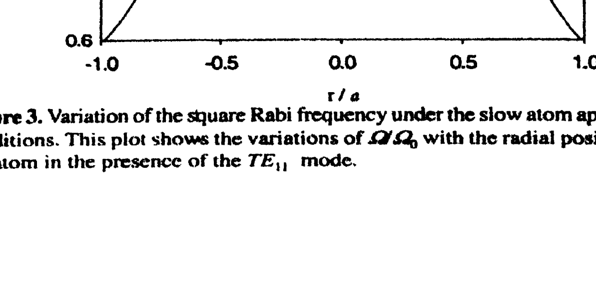

Figure 3. Variation of the square Rabi frequency under the slow atom approach conditions. This plot shows the variations of Ω/Ω_0 with the radial position of the atom in the presence of the TE_{11} mode.

the potential will exhibit a maximum at these points for a negative detuning. The results shown in Figures 4 and 5 depict the evolution of the longitudinal scattering force and the corresponding radial potential distribution.

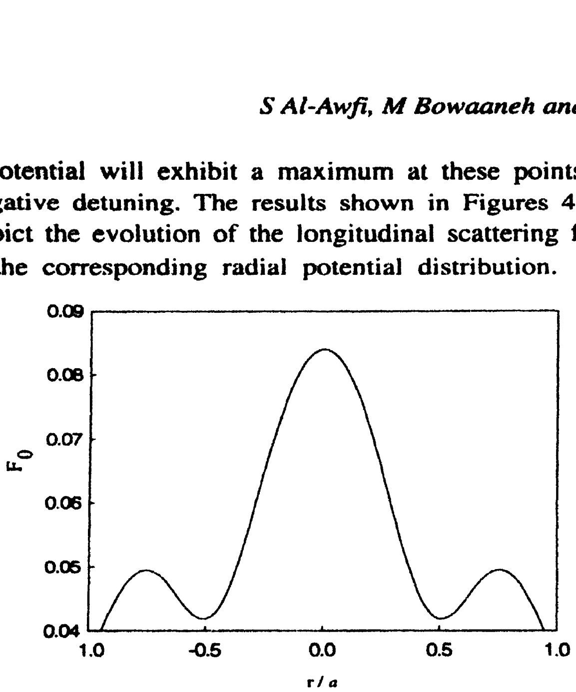

Figure 4. Variation of the spontaneous force under the slow atom approach conditions. This plot shows the variations of F/F_0 with the radial position of the atom. Here, $F_0 = 2\hbar k_{11}\Gamma_0$.

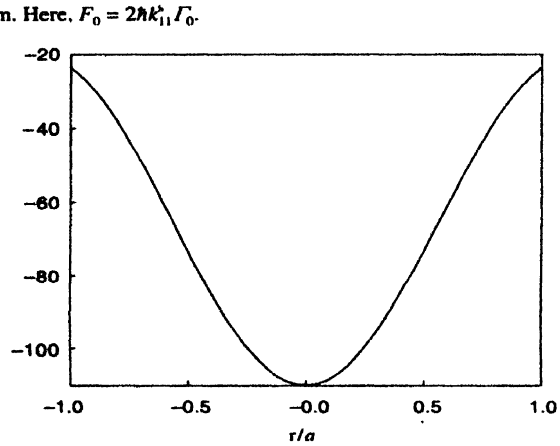

Figure 5. Variation of the optical potential under the slow atom approach conditions. This plot shows the variations of U/U_0 with the radial position of the atom. Here U_0 is defined by $U_0 = \hbar\Gamma_0/2$.

As expected, we see that atoms located at the center, experience the maximum longitudinal scattering force while the dipole potential exhibits a minimum at points where the power has maximum. On the other hand, no longitudinal scattering force exists on the surface while the dipole potential is maximum at the surface.

The longitudinal scattering force will cause a translational motion to the atom along the axis of the optical fiber and the azimuthal scattering force will cause the atom to rotate. Ultimately, and assuming the above the parameters, the potential depth is roughly about $110U_0$ which is adequately deep to permit trapping leading to a radial oscillatory motion of the atom.

5.3. Atom trajectories :

To investigate the trajectories of an atom put in the TE_{11} channeling mode, we need to solve the classical equation of motion, given as

$$M\frac{dr^2}{dt^2} = F_{SC.} + F_{RE.} \tag{20}$$

We have neglected the influences of the van der Waals force [17], because, it is effective only at a vary short length from the surface. It is also easy to see that F_{RE} can act as an attractive force in the high power area provided the detuning Δ_0 is negative.

In Figure 6, we plot the trajectory of a sodium atom with the above parameters and under the initial conditions in which the atom starts from rest at the point $x = y = 0.5\lambda$. Such an atom moves under the influence of both scattering force and dipole force. This channelling (or heating) of the longitudinal motion is clearly evident in the z-direction, leading to a very weak trapping of atom in the high power region. Figure 6 shows very clearly that the movement of atom is a superposition of translational and radial motions.

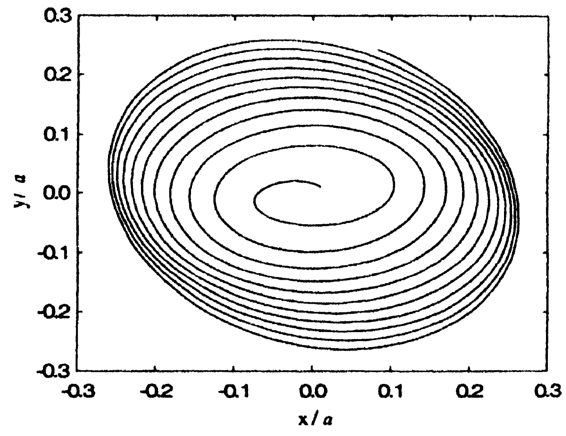

Figure 6. Predicted transverse trajectory of the atom under the slow atom approach conditions in the presence of the TE_{11} mode.

The motions are due to the longitudinal scattering, the azimuthal scattering and the dipole forces respectively. An important feature displayed by the results depicted in Figure 6 is that the sign of the angular momentum quantum number changes from (+1) to (−1), causing rotational motion to switch from clockwise to anti-clockwise.

6. Conclusions

The main objective of this study is to investigate the atom moving within an optical fiber with a hole diameter of the order of the 2–10 μm. This system is exact mono-mode fibre operation where only the fundamental mode with cut-off frequency $f_{11} \approx 0.3$ PHz is allowed to propagate and thus the dipole emission may take place only by one mode. Hence, the atom propagation maintains coherence which is very useful for the application of atom interferometry. We have considered the configuration of Ol'Shanii *et al* [8] based on the grazing incident mode. Thus, the laser frequency was tuned to the red side to attract the atoms to the high power region at the centre of the hollow optical fibre.

We have used the slow atom approach to emphasise the role of an excited mode in determining the average adjustment of the dipole moment vector of an atom moving inside the fiber in case of TE_{11} mode excitation. With this configuration, the dipole emission rate at any given point in the optical fiber, becomes that of a dipole adjusted along the direction of the electric mode vector at the given point. This apparent dipole emission rate distribution in the optical fiber is the main important result of this approach. Another important result is the distribution of the Rabi frequency leading to the determination of light forces by this approach.

We have examined these results of the slow atom approach in the context of the channeling atom. The dipole emission distribution across a hole diameter of the fiber has been evaluated, which gives clear indication of the slow atom approach effect. By way of illustration, near the fiber wall, the direction of the dipole is purely normal to the fiber surface because the electric field vector is purely normal to the axis. Thus, the value of the dipole emission rate is $2\Gamma_0$. For a dipole located along the fiber wall and its axis, the angle θ_{11} changes in the way displayed in Figure 1. The dipole emission rate in Figure 2 reflects this change in the dipole adjustment in the zone. The analogous distributions of the Rabi frequency have been examined as well.

We have explored the nature of the light forces and their influence on atomic motion for an atom moving inside a mono-mode optical fiber. We have shown that the longitudinal scattering force is responsible for a translational motion of the atom along the axis, the azimuthal scattering force is responsible for a rotational motion and the dipole potential is responsible for restraining the atom in given regions of the optical fiber. The effect of the slow atom approach on the atom trajectories is investigated for the specific case involving sodium atoms in a mono-mode optical fiber and the result is displayed in Figure 6. We conclude that such fiber mode generates a potential arising from dipole force while the scattering force provides a mechanism to channel (heat) and to rotate the atom. Moreover, the orbital angular momentum (OAM) of such a mode is explicit and its influence on atomic motion is more straightforward to interpret.

References

[1] C Adams, M Sigel and J Mlynek *Phys. Rep.* **240** 145 (1994)

[2] A Aspect *Phys. Rep.* **219** 141(1992)

[3] C Adams and M Sigel *Prog. Quant. Elecrton* **21** 1 (1997)

[4] F Wright, P Jessen and G Lapeyere *Opt. Commun.* **129** 423 (1996)

[5] H Ito, K Sakaki, T Nakata, W Jhe and M Ohtsu *Opt. Commun.* **115** 57 (1995)

[6] S Marksteiner, C Savage, P Zoller and S Rolston *Phys. Rev.* **A50** 2680 (1994)

[7] S Al-Awfi and M Babiker *Phys. Rev.* **A58** 4768 (1998)

[8] M Ol'Shanii, Y Ovchinnkov and V Letokhov *Opt. Commun.* **98** 77 (1993)

[9] C Savage, S Marksteiner and P Zoller in *Fundamentals of Quantum Optics III*, F. Ehlotsky (ed.) (Berlin : Springer-Verlag) (1993)

[10] J Ye, D Vernooy, and H Kimble *Phys. Rev. Lett.* **83** 4987 (1999); A Doherty, T Lynn, C Hood and H Kimble *Phys. Rev.* **A63** 013401 (2000)

[11] J M Senior *Optical Fibre Communication Principle and Practices* (2nd edn.) (Hemel Hempstead : Prentice Hall) (1992)

[12] O Stern *Physik.* **61** 95 (1929)

[13] A Ashkin *Phys. Rev. Lett.* **24** 156 (1970)

[14] M Renn, D Montgomary, O Vdovin, D Anderson, C Wieman and E Cornell *Phys. Rev. Lett.* **75** 3253 (1995)

[15] M Renn, E Donley, E Cornell, C Wieman and D Anderson *Phys. Rev.* **A53** R648 (1996)

[16] H Ito, K Sakaki, M Ohtsu and W Jhe *Appl. Phys. Lett.* **70** 2496 (1997)

[17] S Al-Awfi and M Babiker *Phys. Rev.* **A58** 2274 (1998)

[18] H Nha and W Jhe *Phys. Rev.* **A56** 2213 (1997)

[19] N Kapany and J Burke *Optical Waveguides* (London : Academic Press) (1972)

[20] M Rippin and P Knight *J. Mod. Opt.* **47** 807 (1996)

[21] E Hinds *Adv. Atom. Mol. Opt. Phys.* **2** 1 (1993)

[22] C Sukenik, M Boshier, D Cho, V Sandoghdar and E Hinds *Phys. Rev. Lett.* **70** 560 (1993)

[23] S Al-Awfi and M Babiker *Phys. Rev.* **A61** 033401 (2000)

[24] R Loudon *The Quantum Theory of Light* (2nd edn.) (Oxford : Oxford University Press) (1995)